

Accelerator and Transport

D. Raparia

July 25-27, 2005

Acknowledgements



Contributors:

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July 25-27, 2005

EBIS Pre-CD1 Technical, Cost, Schedule, and Management Review



- LEBT
 - RFQ
 - MEBT
 - LINAC
 - HEBT
 - Booster Injection
-

Requirements

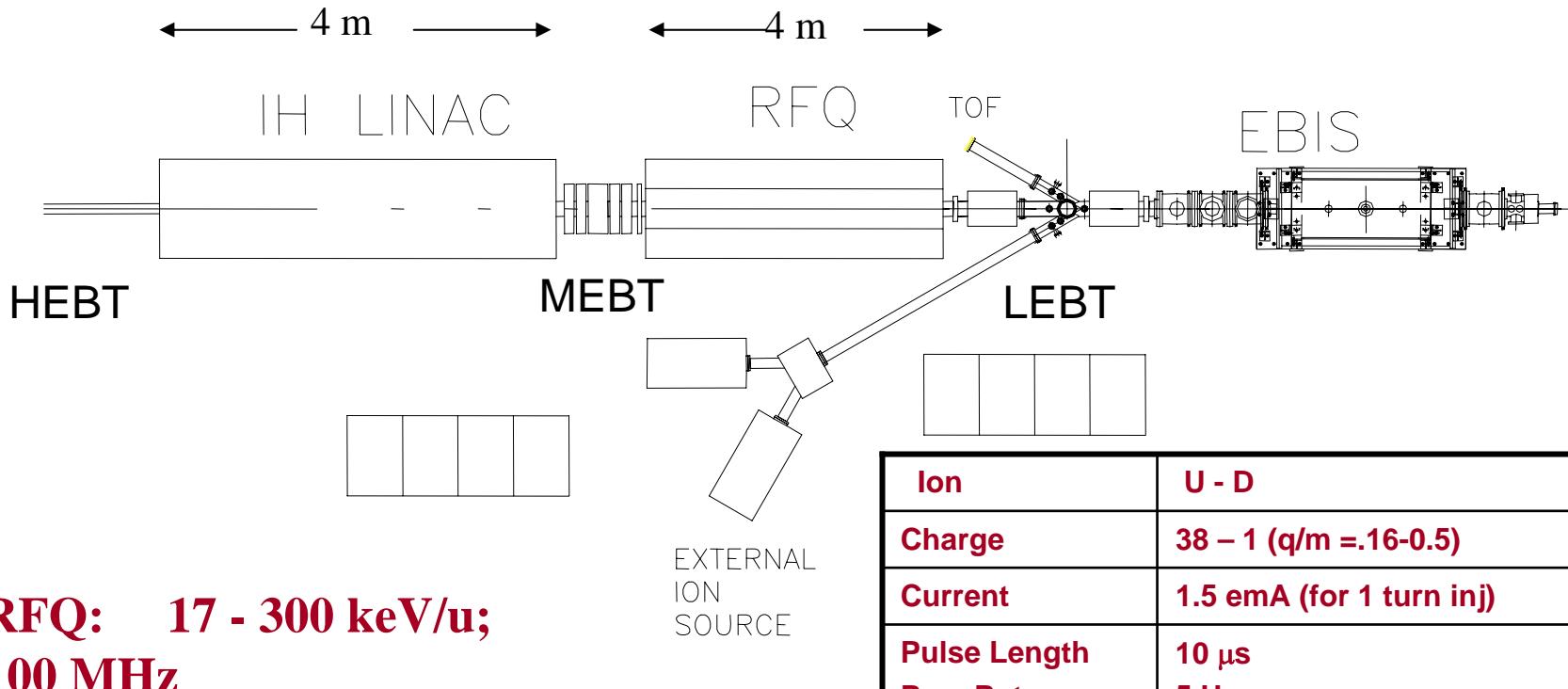
- The EBIS Preinjector should be able to match the performance for ions species which the Tandem presently provides

	Z	A	Q	Q/m	Vext(kV)	I
	(all ch states)					
He3*	2	3	2	0.67	25.5	10
D	1	2	1	0.50	34.0	6
C	6	12	6	0.50	34.0	10
O	8	16	8	0.50	34.0	10
Si	14	28	12	0.43	39.7	10
Fe	26	56	16	0.29	59.5	10
Au	79	197	32	0.16	104.7	10

* Out of EBIS Linac scope

Simulations were carried out for two extreme Q/m namely Au⁺³² and ³He⁺². Only Au³² results will be presented in this talk.

Proposed Linac – Based RHIC Preinjector



Ion	U - D
Charge	38 – 1 ($q/m = .16-0.5$)
Current	1.5 emA (for 1 turn inj)
Pulse Length	10 μs
Rep. Rate	5 Hz
Duty Factor	0.0005 %
Emittance	$0.14 \pi \text{ mm rad}$ (nor, rms)
Energy Spread	1.8 keV/u

LEBT Requirements

- Inject into EBIS
- HV acceleration
- Extract from EBIS
- Diagnostics: Emittance Monitor, Current Monitor(2), TOF
- Matching into RFQ

Twiss parameters at beginning and end of the LEBT for Au⁺³²

Parameters	Beginning of LEBT (2.6 keV/u)	End of LEBT (17 keV/u)	Units
α_x	0	1.057	
β_x	0.075	0.064	mm/mrad
ε_x (rms,N)	0.035	0.070	π mm mrad
α_y	0	1.057	
β_y	0.075	0.064	mm/mrad
ε_y (rms,N)	0.035	0.07	π mm mrad

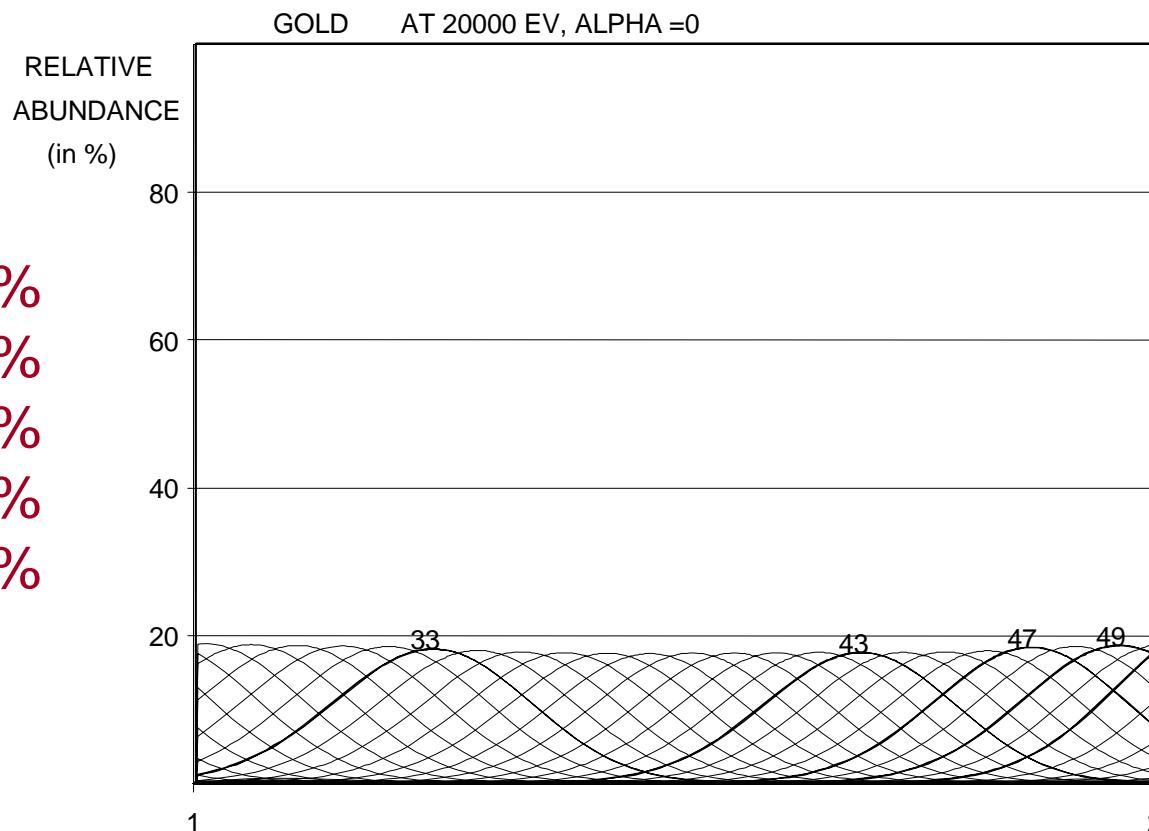
Energy = 2.6 keV/u
 $\beta=0.00236$
 $\gamma=1.0000027$

Energy = 17 keV/u
 $\beta=0.006017$
 $\gamma=1.000018$

Charge State Distribution

Computer calculations of successive ionization of Au with a 20keV electron beam:

Q32	18%
Q31	15%
Q33	15%
Q30	12%
Q34	12%
.....	



Space Charge in LEBT

Current 10 mA

	Z	A	Q	Q/m	Vext	EPS(un)	Perv(gen)	ET	SCT	Ratio	Debye Len
He3	2	3	2	0.67	24.4	326	0.00197	0.0315	0.1314	4.16841	0.002596217
D	1	2	1	0.50	32.5	245	0.001	0.0177	0.0985	5.55788	0.002252987
Si	14	28	12	0.43	37.9	210	0.001	0.0130	0.0845	6.48419	0.002085861
Au	79	197	32	0.16	100.0	79	0.00048	0.0019	0.0320	17.1078	0.001274568

Measurement for 1.7 mA Au⁺³⁵ (n,rms) = 0.1 π mm mrad @ 20keV
 Calculated(n,rms) = 0.12 π mm mrad

EPS(n) = 0.16 * r² * Bz * (Q/M) pi m-rad, R=0.002 m, Bz=4.6 T

Envelope equation $R'' + k_0^2 R - \frac{(4\mathcal{E}_{rms})^2}{R^3} - \frac{K}{R} = 0$

Gen. Perv. (K)= QI/(2 π ε₀ m c³ β³γ³)
 Debey Length(λ_D) = 2 ε²_{rms}/K=(1/8)(R/λ_D)²

Energy = 17 keV/u
 β=0.006017
 γ=1.000018
 R= 15 mm

LEBT Current Limit

- Distance needed between two lenses for external ion injection (L) ~ 0.67 m.
- Beam radius (R) ~ 3.4 cm, Lenses (solenoid) aperture radius 4.8 cm
- Maximum beam current for SC dominated drift (L), maximum beam radius (R) and initial slope $R'_0 = -0.92$ given by

$$I_{\max}(A) = 1.166 * (mc^2 / 30 * q) * \beta^3 \gamma^3 (R/L)^2$$



	I_{\max} (mA)
${}^3\text{He}^{+2}$	31.0
Au^{+32}	124.0

Starting Conditions for LEBT (A.Pikin)



Input parameters are generated using formula below for ion extraction/acceleration for LEBT

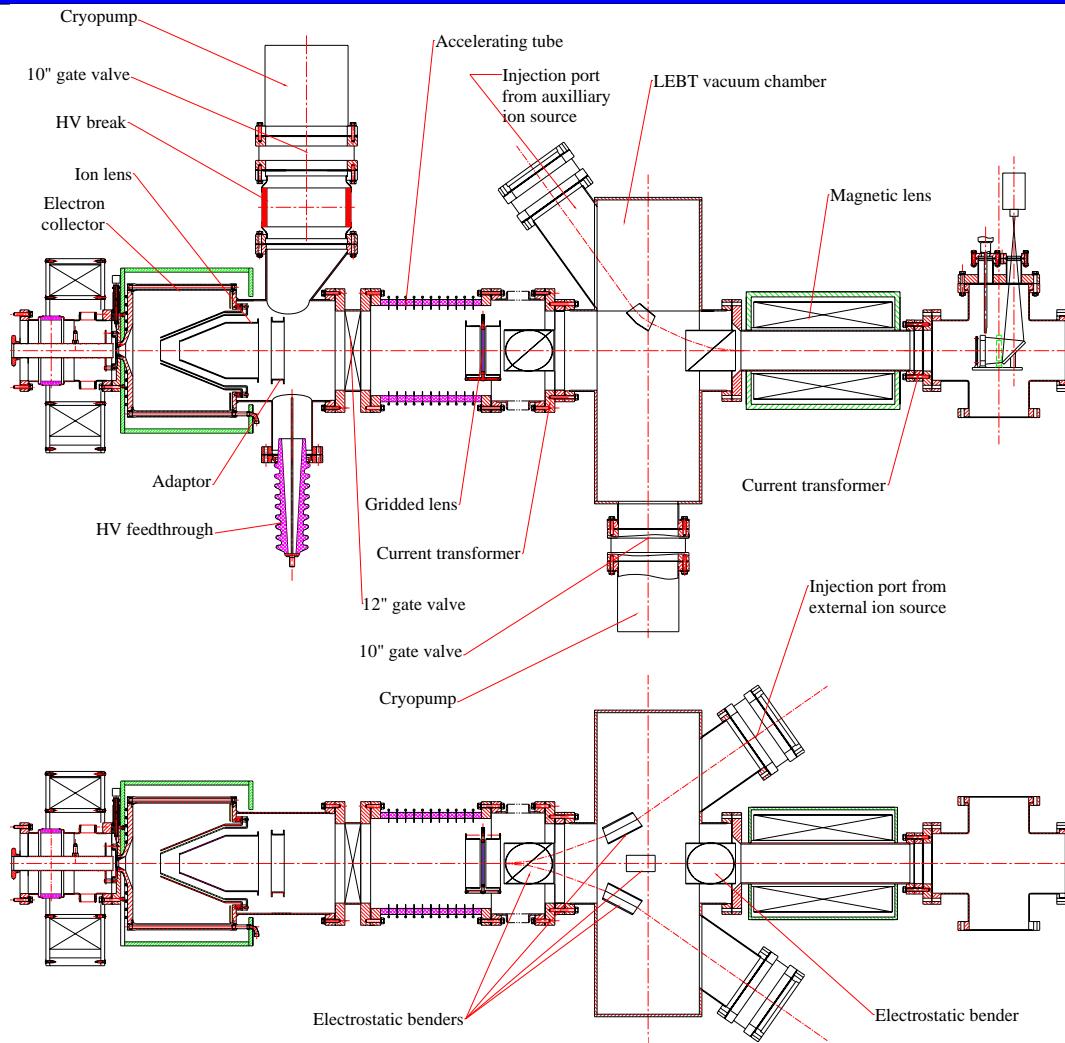
$$kT_i \left(\frac{R_t}{R_i} \right)^2 = q \cdot (U(R_i, z_0) - U(0, z_0))$$

Energy = 2.6
keV/u
 $\beta=0.00236$
 $\gamma=1.0000027$

R_t = radius of ion beam in the trap, R_i = radius of ion beam
 kT_i =transverse ion temperature

	E (KeV)	α	β (m)	ε (rms, norm) π mm mrad
Au ⁺³² (10 mA)	512	0	0.075	0.035
³ He ⁺² (10 mA)	7.875	0	0.047	0.034

LEBT Layout (A.Pikin)



LEBT: 2-D Simulation with TRAK (A.Pikin)

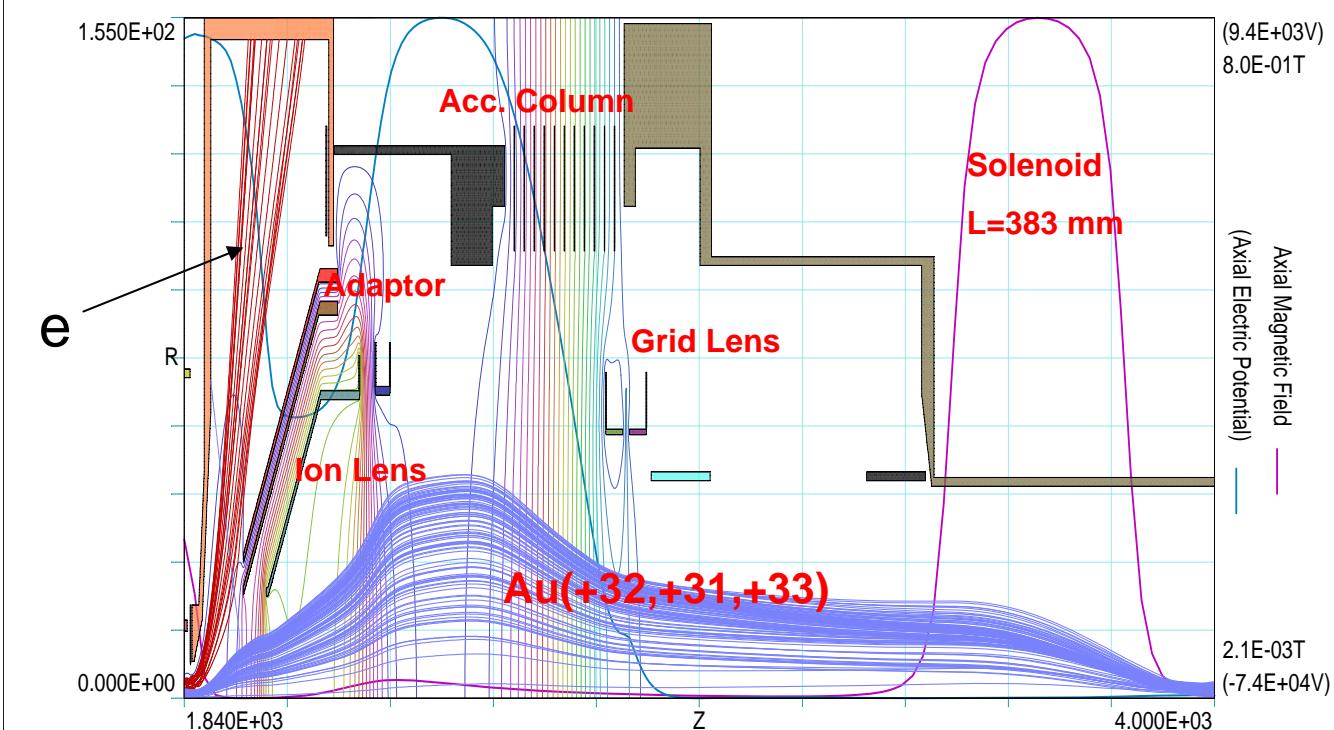
- Maximum distance between lenses to 0.67 m
- Four tuning knobs

This Plot Created On:
July 20, 2005 at 12:24:40

Ion beam: Au^{31+,32+,33+},
I_{ion31+}= 5mA, I_{ion_32+} =5mA, I_{ion33+}=5mA
I_{ion_total}=15 mA
I_{el}=10 A
kT_{i_ion}=20 eV*q
E_{ion_init}=16 keV*q
U_{platform}=84 kV, U_{ion lens}=-50 kV
U_{grid lens}=+10 kV, IN_{magnet lens}=2.2E5 A*T

Ex_{rms} n₃₁₊=0.0788 mm*mrad
Ex_{rms} n₃₂₊=0.0788 mm*mrad
Ex_{rms} n₃₃₊=0.0630 mm*mrad

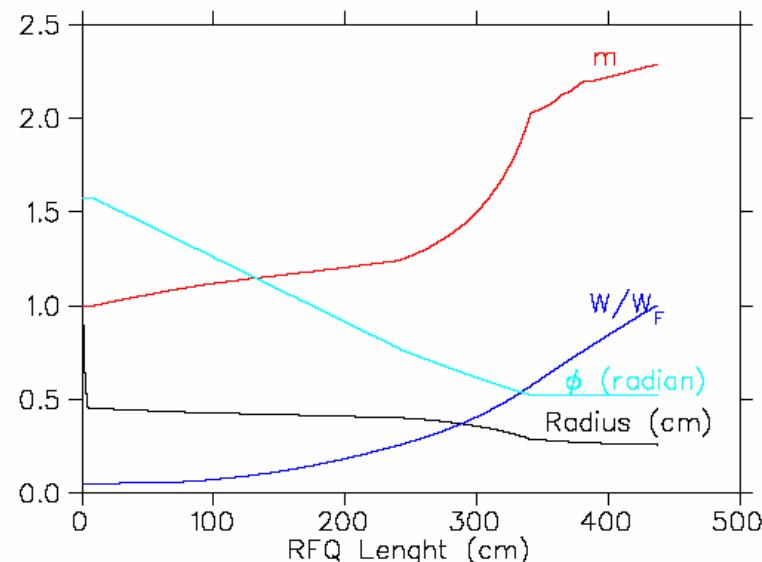
Ion Current 15mA
Platform 84kV
Ion Lens -50kV
Grid Lens 10kV
Solenoid 8kG



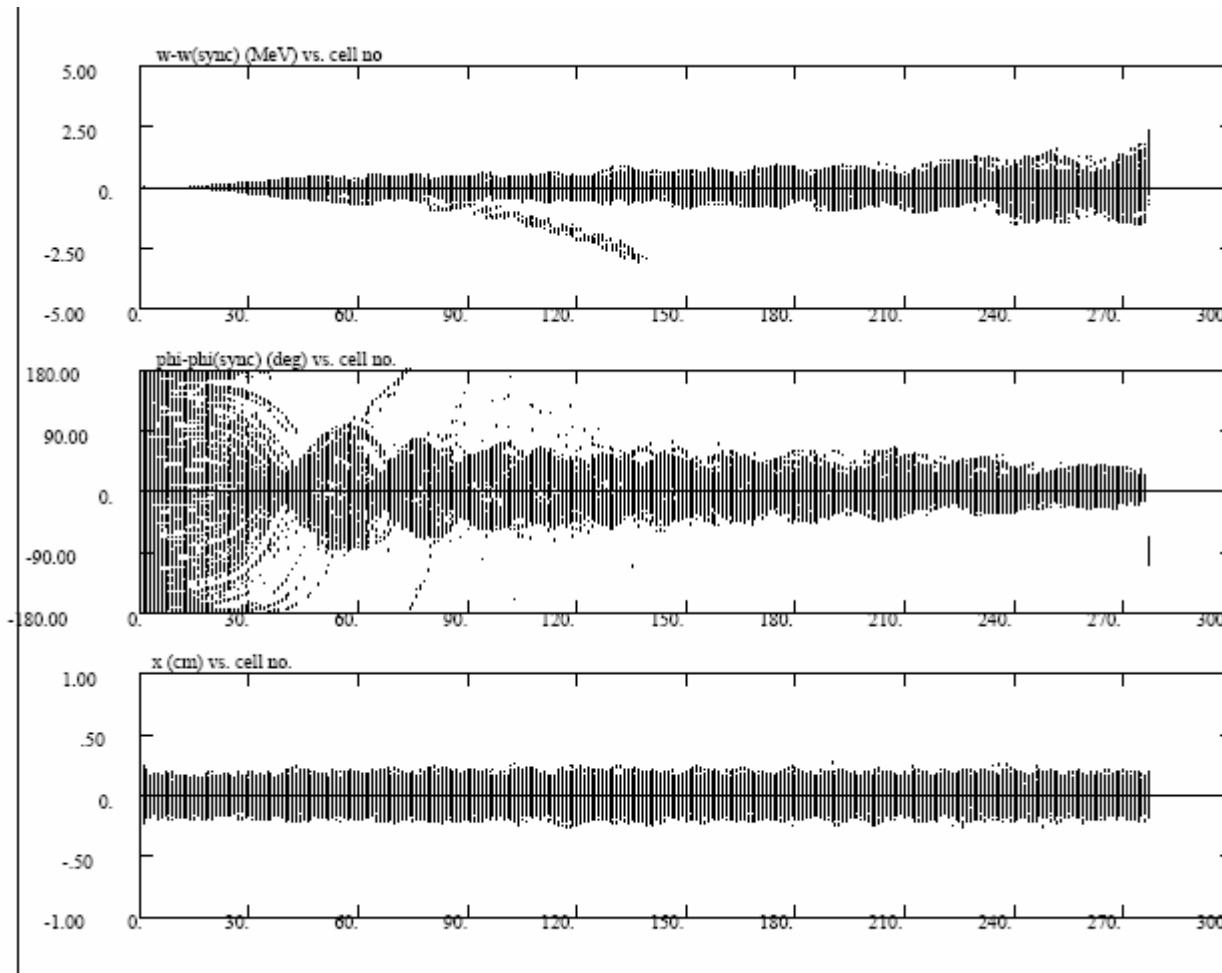
RFQ Parameters

Parameters	BNL	CERN	Units
Type	4-rod	4-rod	
Q/m	0.16-0.5	0.12	
Energy in	17.0	2.5	keV/amu
Energy out	300	250	keV/amu
Frequency	101.28	101.28	MHz
Max rep rate	5	10	Hz
Length	4.37	2.5	Meters
# of cells	277		
Aperture	0.005	.0045	Meters
Voltage	69	70	kV
E (surface)	20.8	≤ 23	MV/m
RF Power	< 350	< 350	kW
Acceptance	1.7	> 0.8	π mm mrad (nor)
Input Emit.	0.35		π mm mrad, nor, 90%
Output Emit. (trans)	0.375		π mm mrad, nor, 90%
Output Emit. (longit)	32.5		π MeV deg
Transmission	91	93	%
Bravery factor	1.8	≤ 2	Kilpatrick

-Could accelerate d- U
- $q/m = .16-0.5$

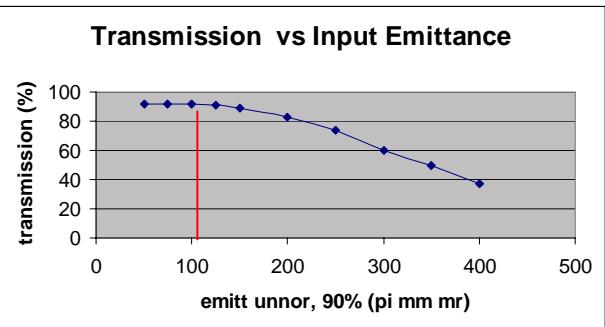


RFQ Beam Dynamics Design, PARMTEQ

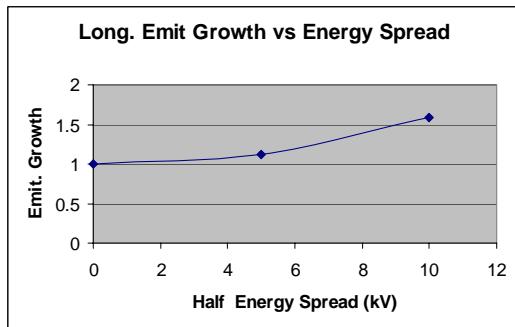


Transmission:
 Au^{+32} **91% (10 mA)**
 d **91 % (10 mA)**
 ${}^3\text{He}^{+2}$ **88% (2 mA)**

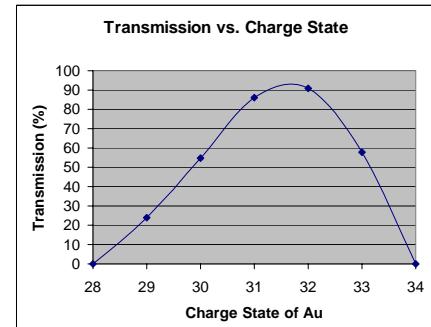
RFQ Transmission



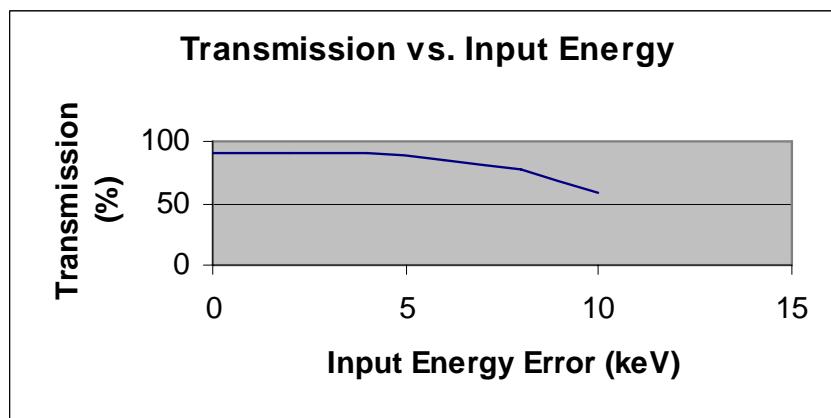
RFQ transmission
vs. Input Emittance



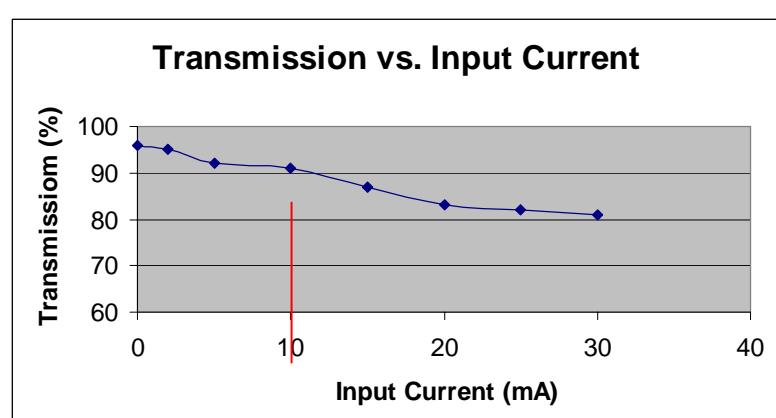
Long. Emittance Growth
vs. energy spread



RFQ transmission for different
charge state of gold



RFQ transmission vs input voltage error
(Nominal operating voltage 100 kV)

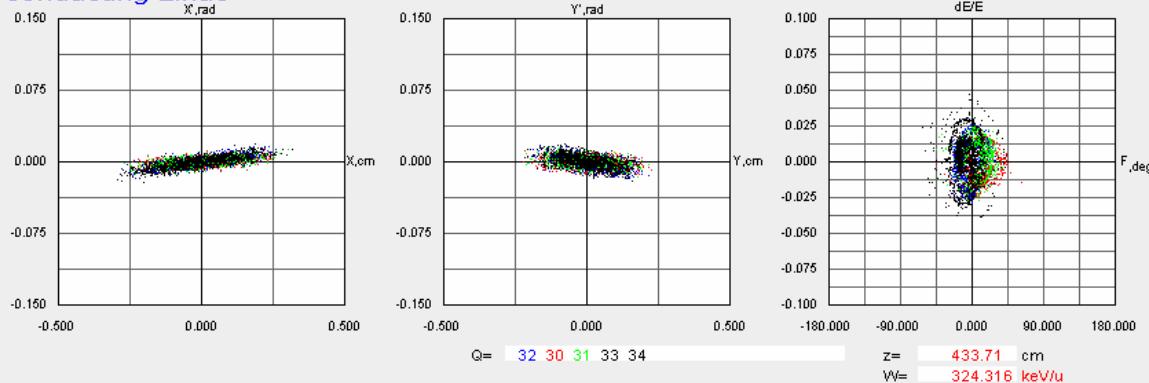


RFQ Transmission vs. input current

Multi-Component Ion Beam Simulation (ANL Code)

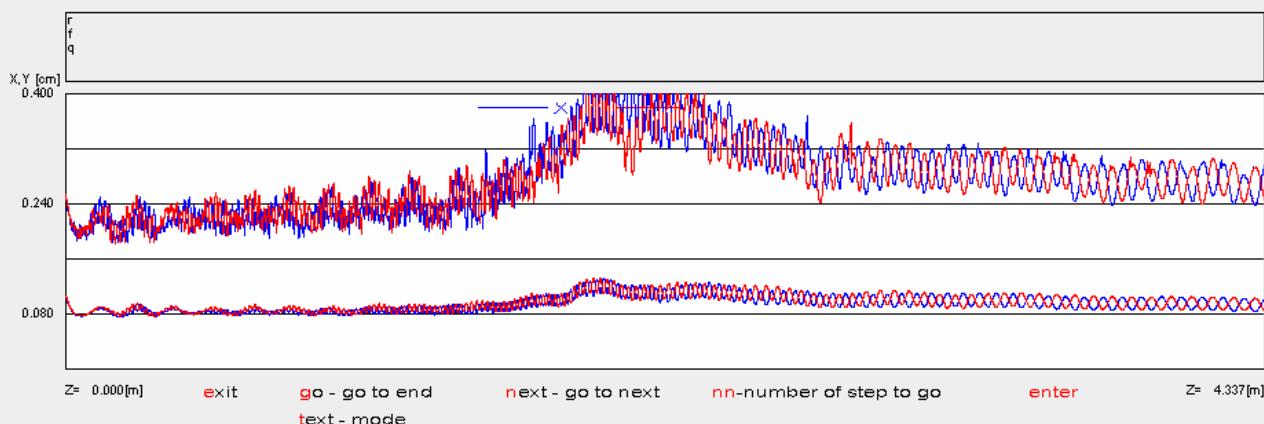


Superconducting Linac



Transmission:
(10 mA)

Q30	52%
Q31	80%
Q32	96%
Q33	85%
Q34	52%



$\Delta\epsilon_t$	(%)
Q30	7
Q31	1
Q32	1
Q33	10
Q34	12

Requirements for MEBT

- Matching from FODO (RFQ) to axial symmetric IH structure with quad triplet
- Diagnostics; Current monitors(2) , Emittance

Twiss parameters at beginning and end of the MEBT for Au+32

Parameters	End of RFQ	Entrance of IH	Units
α_x	1.8	1.802	
β_x	0.18	1.01	mm/mrad
ε_x (rms, norm)	0.11	0.11	π mm mrad
α_y	-1.39	0.60	
β_y	0.142	0.59	
ε_y (rms, norm)	0.11	0.11	π mm mrad
α_z	0.054	0.59	
β_z	0.0203	0.0009	deg/keV
ε_z (rms, norm)	6834	6834	π deg keV

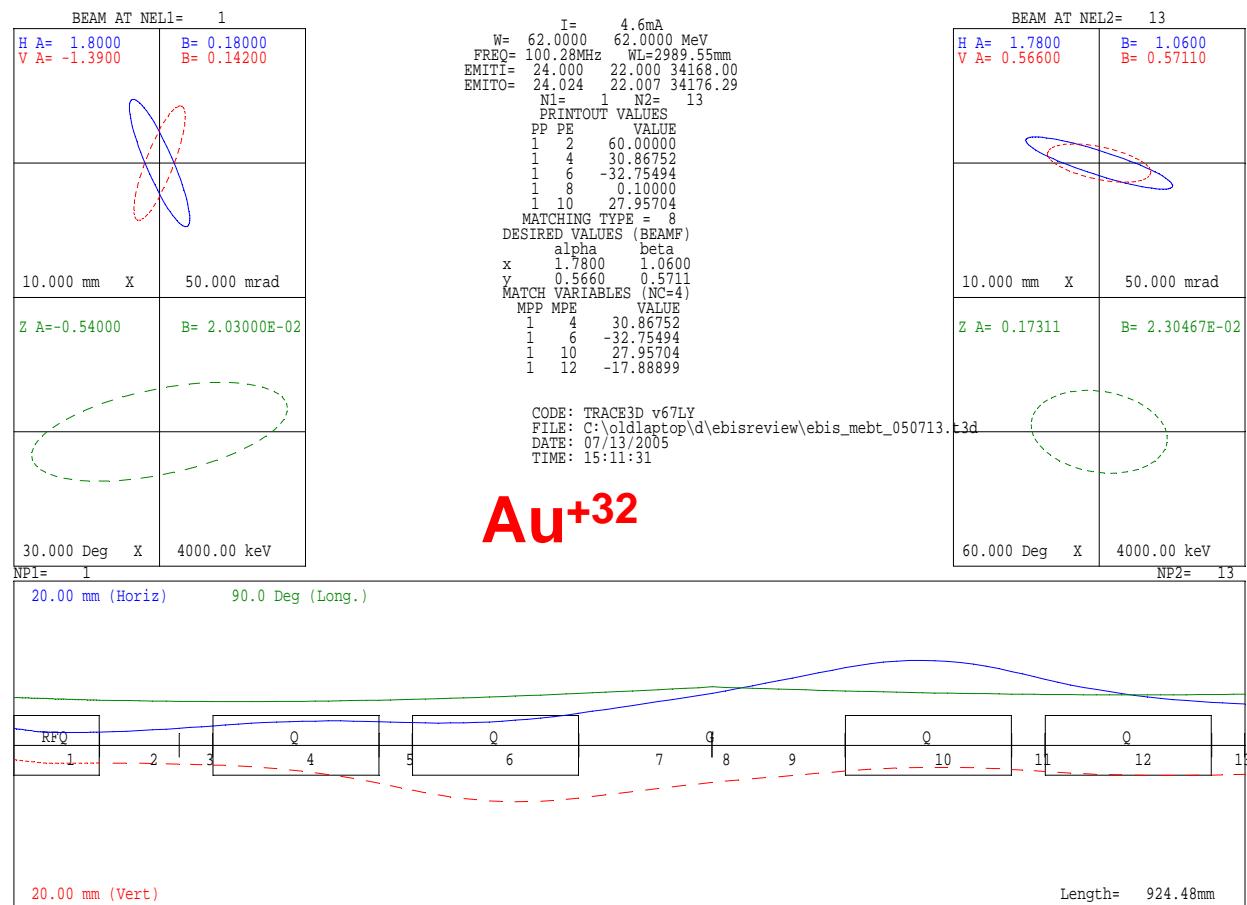
Transport from RFQ to Linac



(4 quads, 1 buncher) RFQ Transition cell

Q2 (EM)	33 T/m
Q3 (EM)	38 T/m
Q4 (EM)	36 T/m
Q5 (EM)	38 T/m
B1	150 kV

EM quads same as
LANL LEDA quads



Au⁺³²

Au⁺³² Au⁺³¹ Au⁺³³ Au⁺³⁰ Au⁺²⁹
 $XI = 1.8 * 0.9 + 1.5 * 0.86 + 1.5 * 0.58 + 1.2 * .55 + 0.8 * .24 = 4.6 \text{ mA}$



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The IH Linac is very similar to the first tank of the CERN Pb linac, our baseline:

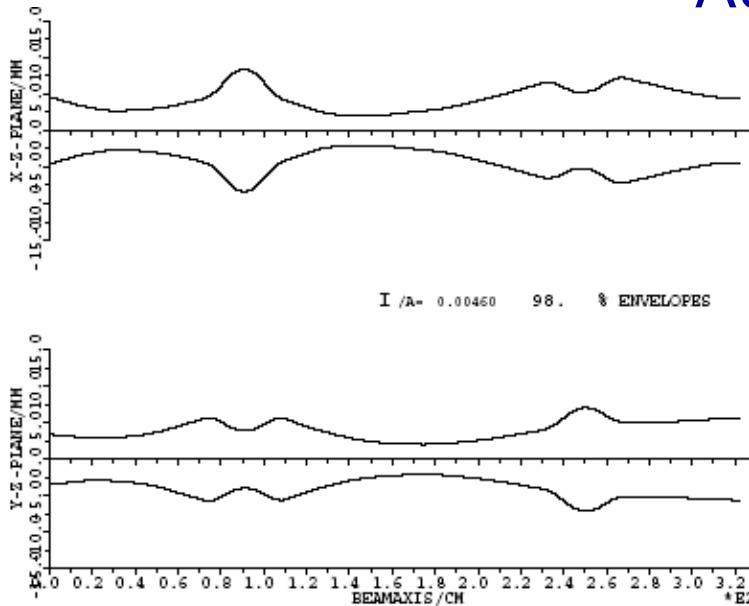
◦ Main parameters of the IH linac

Parameters	BNL	CERN Tank 1	Units
Q/m	0.18-0.5	0.12	
Input energy	0.300	0.250	MeV/amu
Output Energy	2.0	1.87	MeV/amu
Frequency	101.28	101.28	Mhz
Max rep rate	5	10	Hz
length	4.0	3.57	Meters
Input emittamce	0.55		pi mm mrad, norm,90%
Output emittance	0.66		pi mm mrad, norm,90%
Output energy spread	20.0		keV/amu
transmission	100		%

IH linac optics codes LORAS used in the preliminary design



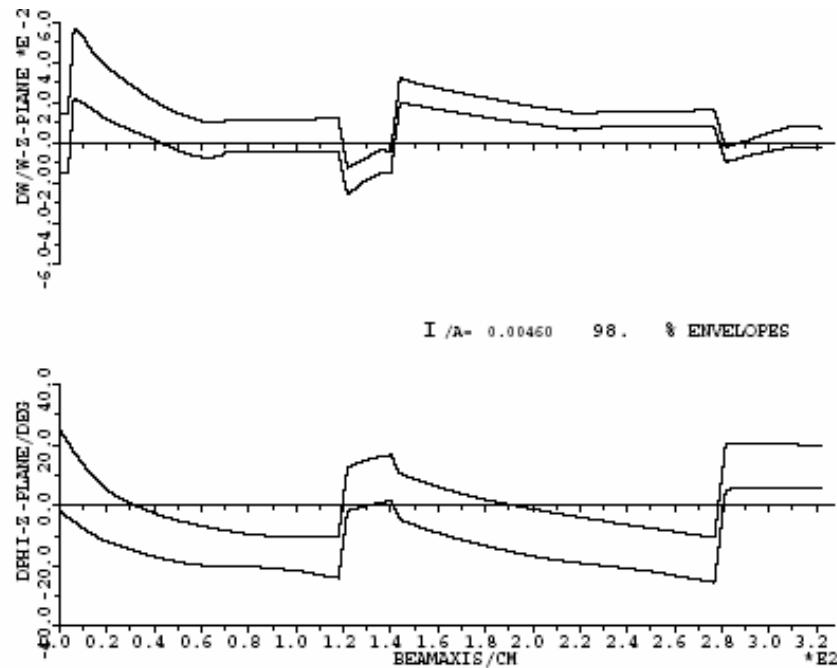
Au⁺³²



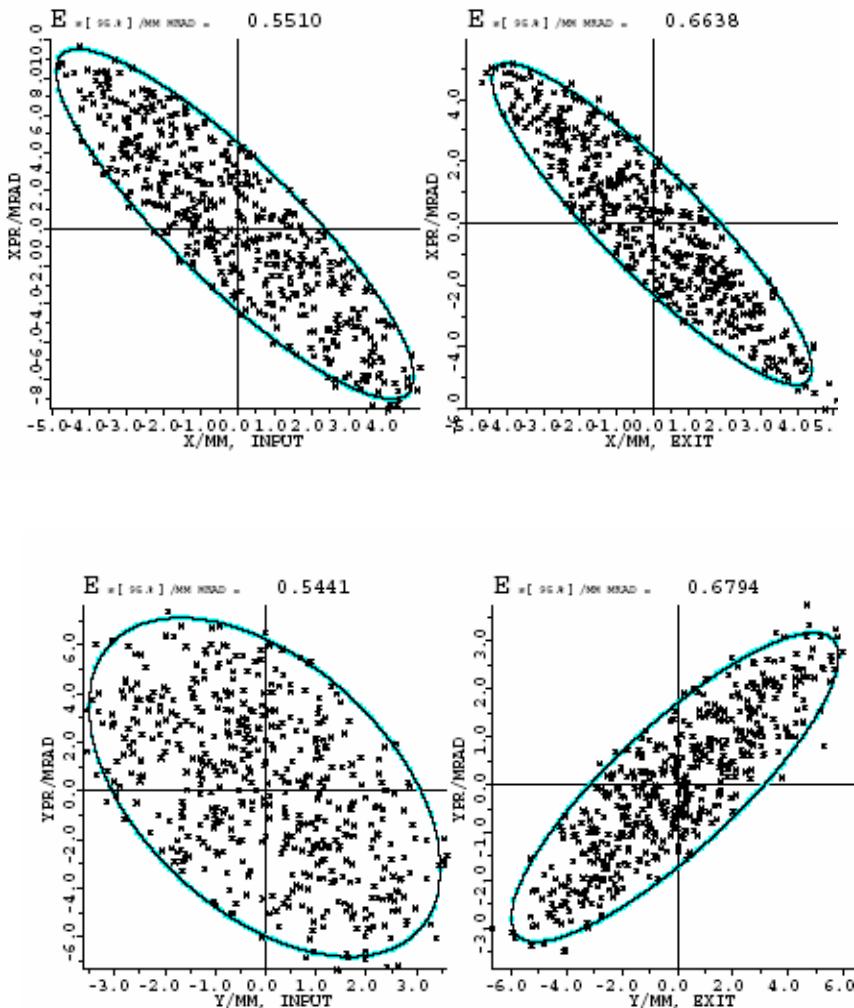
Transverse profiles in the IH linac

Current = 4.6 mA

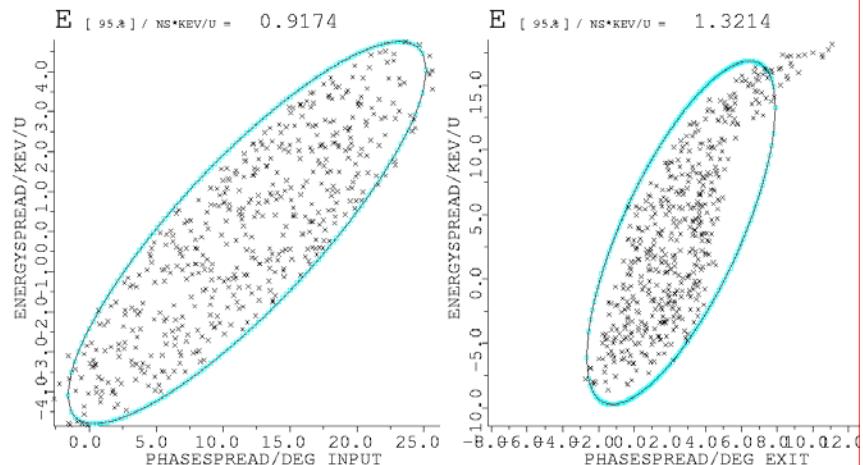
Longitudinal profiles in the IH linac



IH Linac Input and Output Emittances



Au^{+32}



$I=4.6 \text{ mA}$

$X-\text{XP}(\pi \text{ mm mrad})$
 $Y-\text{YP} (\pi \text{ mm mrad})$
 $\phi-\Delta E(\pi \text{ ns/keV/u})$

	Input N, rms	Output N, rms	$\Delta\epsilon$ %
$X-\text{XP}(\pi \text{ mm mrad})$.11	.13	20
$Y-\text{YP} (\pi \text{ mm mrad})$.11	.13	20
$\phi-\Delta E(\pi \text{ ns/keV/u})$.18	.26	41

Emittance for Linac

(Au⁺³²)



	Energy (keV/u)	β	Accpt. (N) (π mm mrad)	Transverse ε (N, rms) (π mm mrad)		Longitudinal (rms)	
				Simulation Input	Simulation Output	ε π MeV deg	ΔE kev/u
EBIS- LEBT	2.6-17	0.0060		-	0.125	-	-
RFQ	300	0.025	1.7	0.125	0.125	6.5	1.34
IH Linac	2000	0.065	4.3	0.125	0.153	7.0	8.9
Inflector	2000	0.065	1.9	0.153	0.153	7.0	0.804*

**Measurements: 0.1 π mm mrad (n, rms)
Au⁺²⁵ (all charge states) 1.7 mA**

*Booster requirement 0.89 keV/u

Though simulations show only 22% transverse emittance growth,
we have designed for 100% emittance growth from EBIS to Booster.

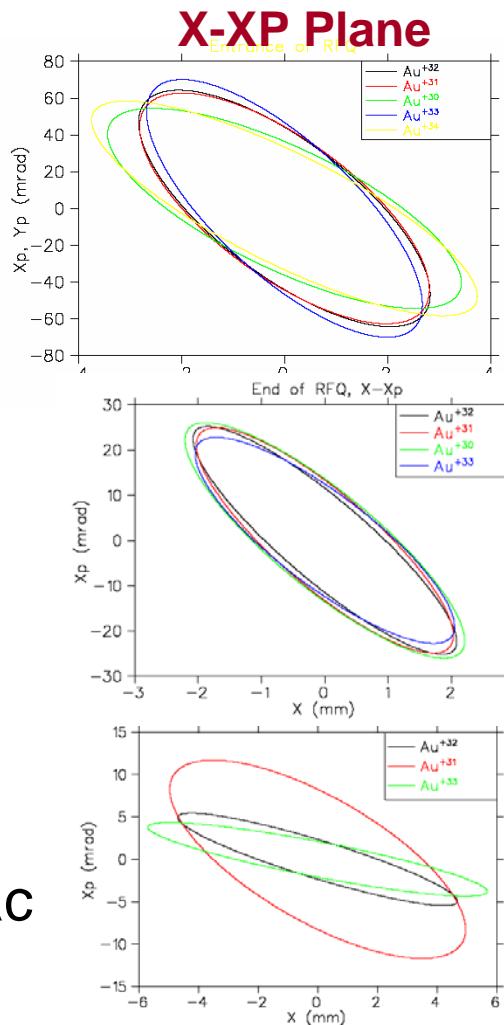


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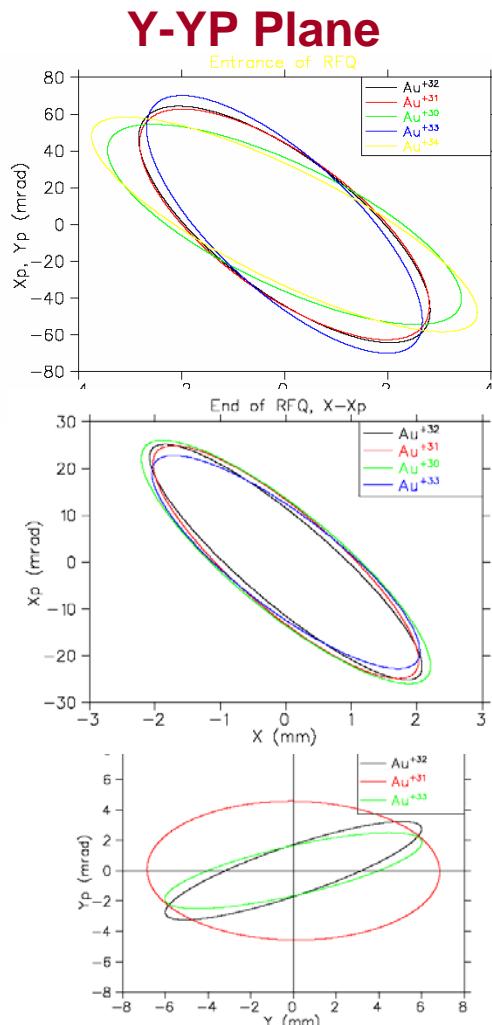
Phase Space Plots for Different Charge States of Au



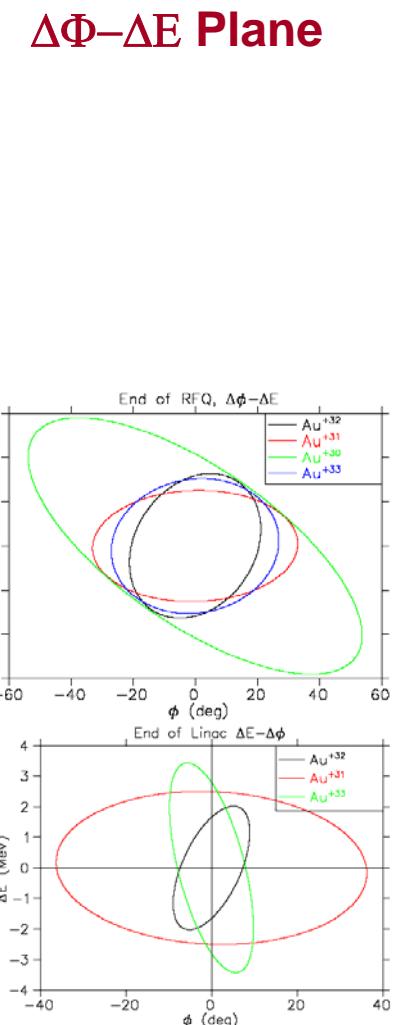
LEBT



RFQ



IH Linac

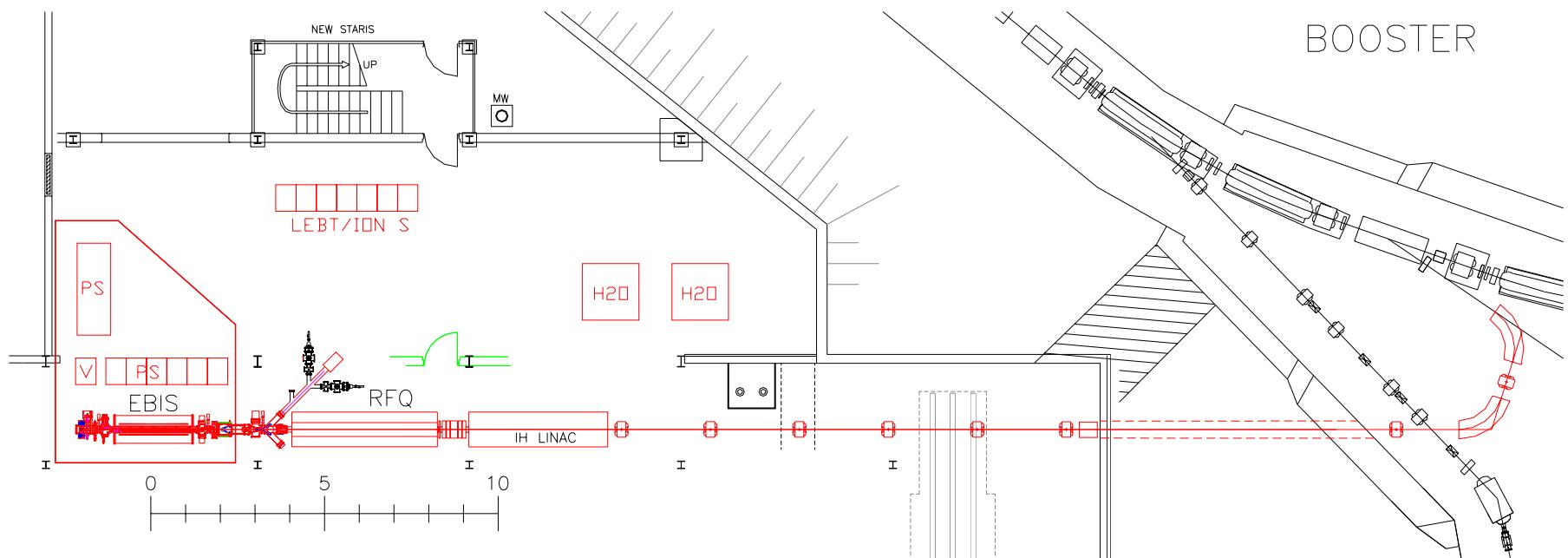


Requirements for HEBT

- Transport beam to Booster
 - Mismatch beam into Booster to avoid scraping at inflector and to reduce Incoherent tune spread in the Booster.
 - Minimize energy spread at the injection, $d\mathbf{p}/\mathbf{p} = \pm 0.05\%$,
 - Provide ion charge state Discrimination
 - Diagnostics: Current Monitors (2), Multiwire/Faraday cups (3), Fast Faraday cup
- Twiss parameters at beginning and end of the HEBT**

Parameters	End of IH Linac	Entrance of Booster	Units
α_x	2.1	-1.87	
β_x	3.0	2.5	mm/mrad
ϵ_x (rms, norm)	0.153	0.153	π mm mrad
α_y	-1.59	0.8	
β_y	3.45	4.8	mm/mrad
ϵ_y (rms, norm)	0.153	0.153	π mm mrad
ΔE (rms)	± 602	± 162	keV (Au^{+32})
ΔE (rms)	± 16.8	± 6.6	keV (${}^3He^{+2}$)

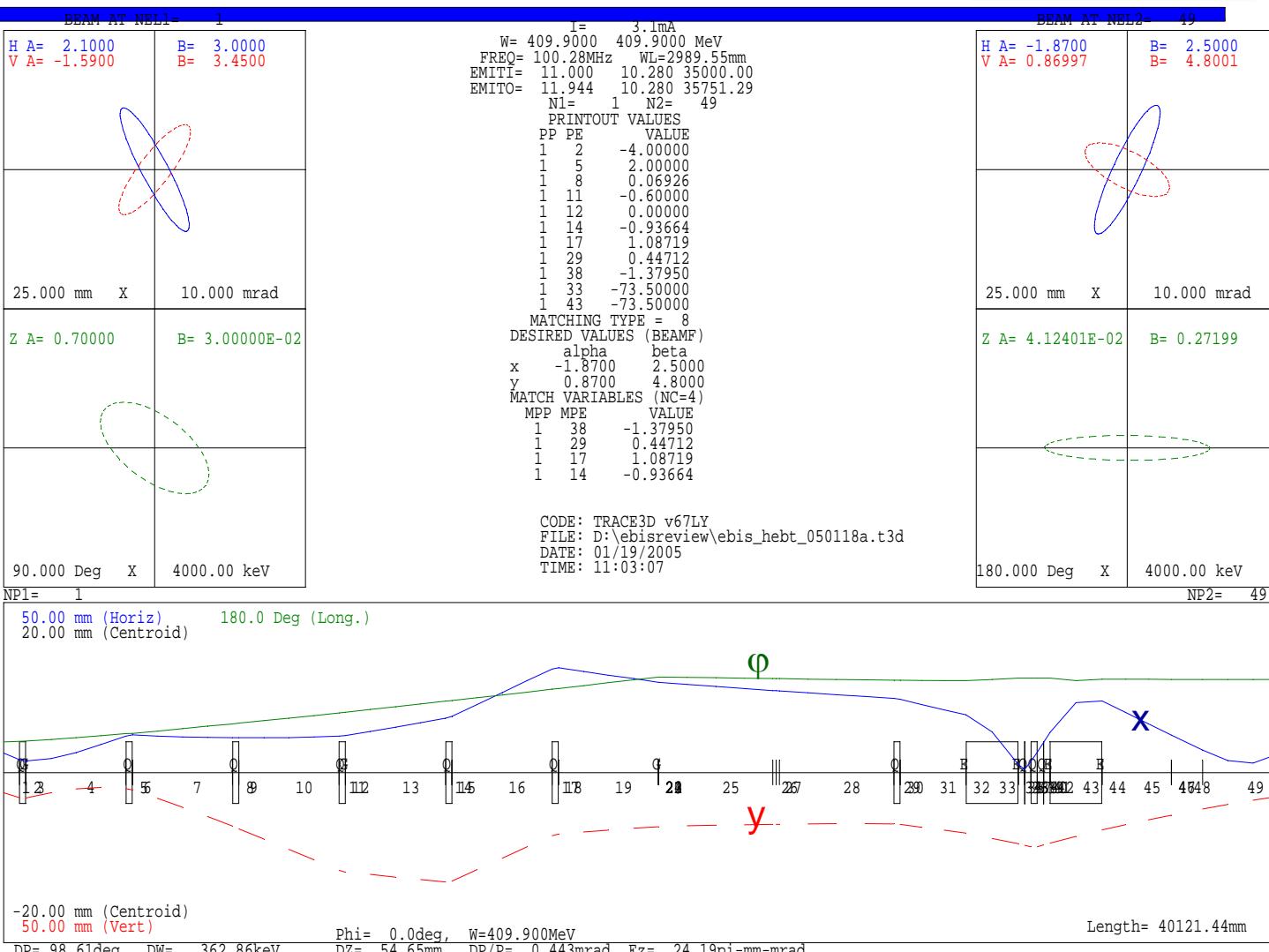
Layout in the Linac Lower Equipment Bay



Optics of the Transport line to the Booster

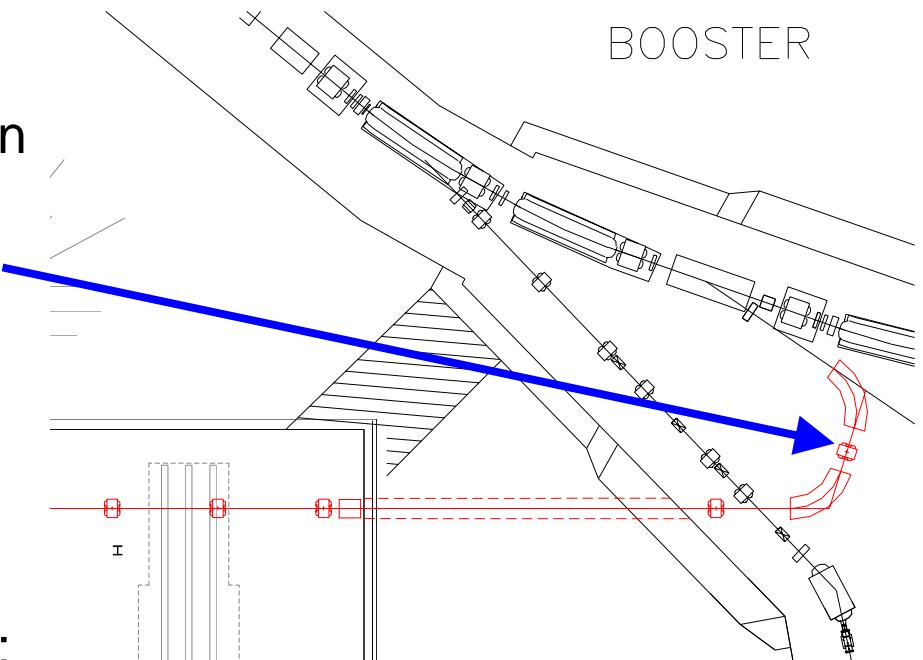
Quad#	G
	T/m
1	4.0
2	2.0
3	0.6
4	0.6
5	1.0
6	1.0
7	0.4
8	1.5

Buncher	V
	kV
1	0
2	33



Charge-state separation

- A beam scraper will be placed at the high-dispersion point between the two HEBT dipoles, to catch neighboring charge states.
- At this location:
 - $R_{16} = 1.1 \text{ mm}$
 - $2r_0 = 2.2 \text{ mm}$
 - Resolution = 500 @ 2 MeV/u;
310 @ 0.3 MeV/u
 - Efficiency = 100%



Tuning procedures with Multiple Charge States

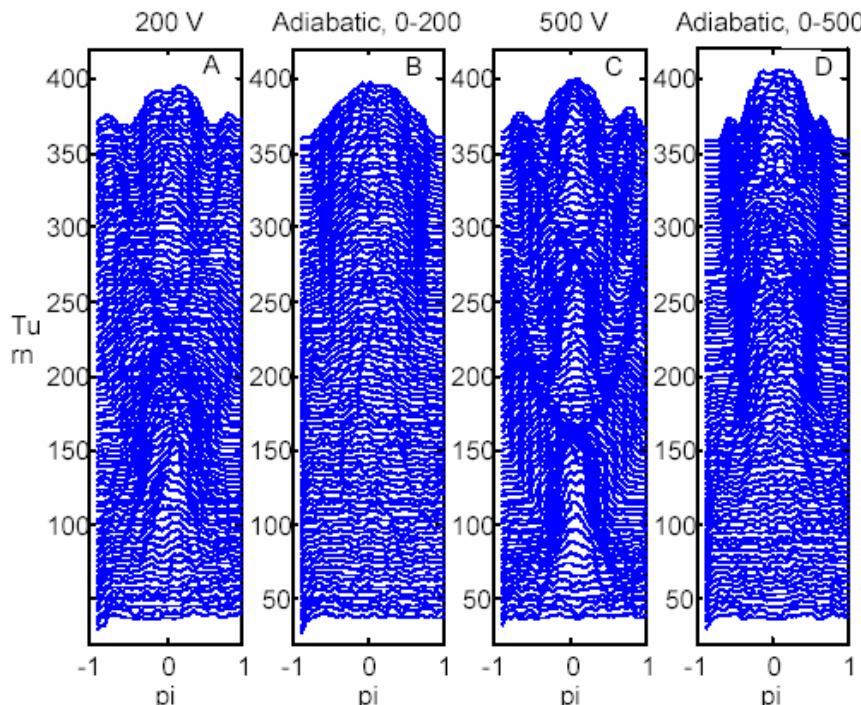


We have studied the tuning procedure for the linac. Summary as follows:

Set all the quads to calculated values and bunchers off

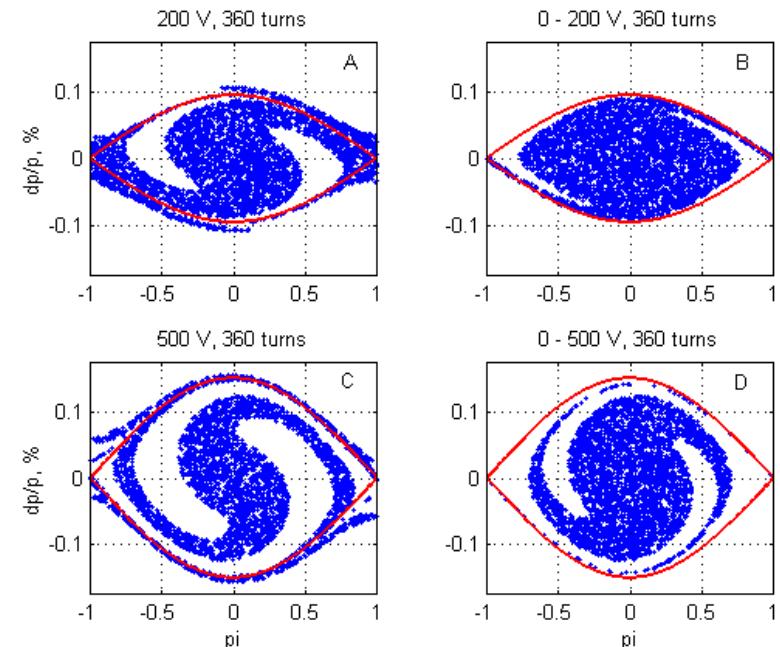
- **LEBT** - with TOF maximize beam current for desired charge state
 - maximize beam current after RFQ to find the match into RFQ
- **RFQ** -since RFQ will be commissioned about 1.5 years earlier than linac, we will set up analyzing magnet to set the correct amplitude (e. g Au^{+32})
- **IH Linac** - to set phase and amplitude of IH Linac, maximize the beam current to desired charge state using Booster
- **MEBT** - maximize current after IH Linac, by tuning quads and buncher
- **HEBT** - minimize the energy spread by tuning buncher amplitude and look at beam size with profile monitor at high dispersion at the bend
 - verify bend magnet setting with Booster

- Transverse:** -For 1-4 turn injection, the calculated incoherent tune spread is 0.62 to 0.16 without any emittance dilution.
- Present 40 turn injection from tandem results in 6 and 3 π mm mrad or 8 and 4 times larger
- Mismatch or off center (smoke ring) to dilute the emittance
- Booster acceptance (VXH)= $70 \times 225 \pi$ mm mrad, 4.5 X15 (Norm)
- Longitudinal:** -Simulation results show EBIS injected beam will have emittance of 0.05 eVs/u or lower (present 0.05 eVs/u)
- Longitudinal microwave instability: Keil-Schnell criteria requires for trans. emit. of 0.7 π mm mrad and energy of 2 MeV/u should have $dp/p > 0.0012\%$ which is satisfied by EBIS beam ($dp/p = \pm 0.05\%$,)



Mountain range of 4 EBIS capture schemes

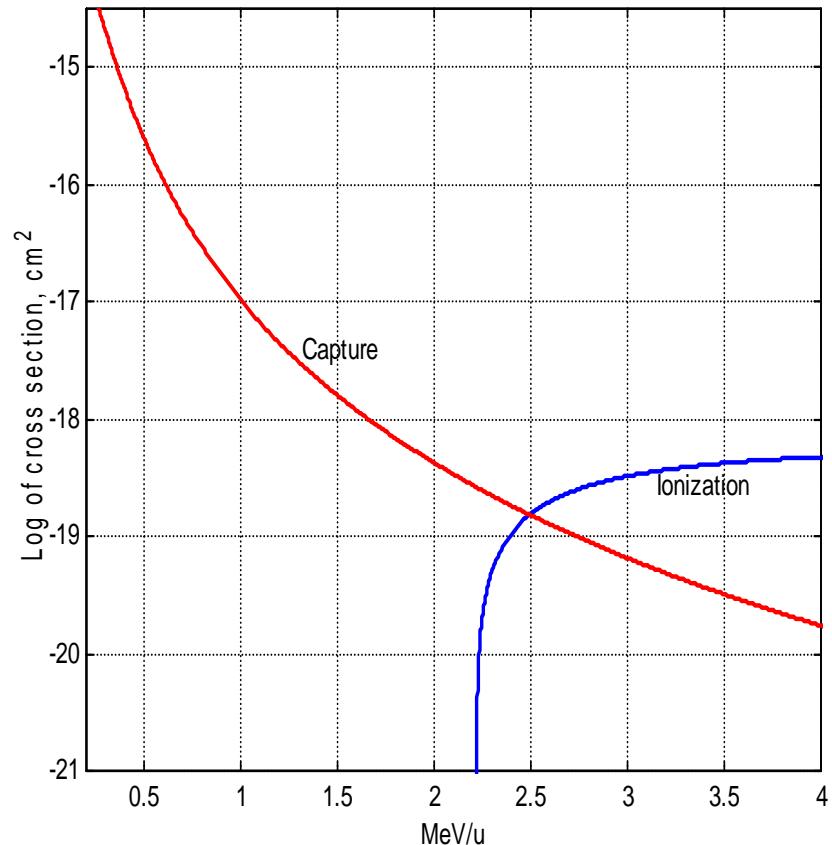
-Adiabatic capture has low losses and lower emittance



Longitudinal Phase spaces after beam capture for 4 schemes

Electron Capture

Electron Capture and Ionization Cross Sections, Au32+



At 2 MeV/u, electron capture cross section reduced by factor of 40 relative to tandem.

Booster Parameters

$$\varepsilon_N = 5 \pi \text{ mm mrad}$$

$$V_{infl} = (G/R)^*(M c^2/Q)^*\beta^2$$

$$\Delta V_{inc} = \frac{-3NQr_0}{2\pi AB_f \beta \gamma^2 \varepsilon_N}$$

	Z	A	Q	Ions/pulse (Bstr input)	Charges/pul	d(nu)	Brho	Inflector
							EBIS	V (kV)
He3	2	3	2	2.14E+11	4.28E+11	-1.60	0.3073	11.53658
D	1	2	1	2.50E+11	2.50E+11	-0.70	0.4097	15.3821
C	6	12	6	2.00E+10	1.20E+11	-0.34	0.4097	15.3821
O	8	16	8	6.70E+09	5.36E+10	-0.15	0.4097	15.3821
Si	14	28	12	5.00E+09	6.00E+10	-0.14	0.4780	17.94579
Fe	26	56	16	1.70E+09	2.72E+10	-0.04	0.7170	26.91868
Au	79	197	32	2.67E+09	8.55E+10	-0.08	1.2612	47.34803
U	92	238	45	1.90E+09	8.55E+10	-0.09	1.0835	40.67711

Note – maximum desired Booster emittance $\varepsilon_N = 10 \pi \text{ mm mrad}$

Emittances



	Vertical π mm mrad (N, 95%)	Horizontal π mm mrad (N, 95%)
Booster*	4.5	10.0
Linac	1.4	1.4
Source	0.7	0.7

*mismatch injection

Note: Booster acceptance (VXH) 4.5 X 15 π mm mrad (N,95%)

Response to January 05 Review



EBIS

- Requires careful measurement of beam parameters
 - ***We will measure the beam parameters after raising the EBIS platform to 100 kV (R&D under progress)***
- A more gentle extraction scheme, instead of proposed fast extraction, may result in minimum longitudinal energy spread
 - ***Within the scope of R&D***

Response to January 05 Review (cont...)



LEBT

- Create a 3D computer model of the LEBT
 - Completed 2D model under single code. Work in progress for 3D model in collaboration with ANL*
- Analyze beam dynamics and compare with beam measurement
 - We will measure emittance under several conditions, comparisons work will begin soon using code from ANL (R&D)*
- Use model to minimize emittance growth
 - Will do that, once comparison work finishes*
- Provide emittance values, energy spread and intensities at RFQ
 - Will do this*



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Response to January 05 Review (cont...)



LEBT

A possible alternate design with bend for LEBT: Its benefits are:

- (a) Reduce space charge in LEBT and Linac
- (b) Reduced rf power to compensate beam loading in RFQ and linac
- (c) Beam tuning

-We have studied the achromatic LEBT for charge separation before RFQ . It could work and have enough dispersion for charge separation

- (a) Simulations show present proposed LEBT and Linac can handle space charge*
 - (b) rf power to compensate beam loading for additional charge is small in comparison to total rf power*
 - (c) Studies show that linac can be tuned with multiple charge states*
- More costly; doesn't seem to be required.*

Response to January 05 Review (cont...)



RFQ and Linac

- Use simulation codes that include the simultaneous transport and acceleration of multi-component ion beam
 - We have the codes from ANL, we are starting these simulations***
- Use last cells of RFQ to optimize the beam matching with MEBT
 - Done***
- Use electric focusing inside IH linac instead of magnetic triplets. BNL can make a later decision depending on the progress in this field
 - We are looking into electric focusing linacs (ANL, Linac Systems). There are not yet any experimental results.***

Conclusions



Will use proven technologies for RFQ and IH structure.

Beam dynamics studies show that the RFQ, LINAC, and matching lines will satisfy all beam requirements.